WE WOULD LIKE TO THANK OUR SUPERVISOR

DR. HAITHAM ZAKI AZZAZI

FOR HIS EFFORTS DURING PREPARING THIS GRADUATION PROJECT .WE REALLY APPRECIATE ALL WHAT HE HAS DONE .

WE WANT ALSO TO EXPRESS OUR RESPECT AND ADMIRATION FOR THE EDUCATION STUFF OF THE ELECTRICAL ENGINEERING DEPARTMENT .

TEAM WORK

(Contents)

CHAPTER 1

INDUCTION MOTOR

CHAPTER 1

AC Induction Motor

1.1 INTRODUCTION

AC induction motors are the most common motors used in industrial motion control systems, as well as in main powered home appliances. Simple and rugged design, low-cost, low maintenance and direct connection to an AC power source are the main advantages of AC induction motors .Various types of AC induction motors are available in the market. Different motors are suitable for different applications. Although AC induction motors are easier to design than DC motors, the speed and the torque control in various types of AC induction motors require a greater understanding of the design and the characteristics of these motors .This application note discusses the basics of an AC induction motor; the different types, their characteristics, the selection criteria for different applications and basic control techniques.

During the last few years the field of controlled electrical drives has undergone rapid expansion due mainly to the advantages of semiconductors in both power and signal electronics and culminating in micro-electronic microprocessors and DSPs. These technological improvements have enabled the development of really effective AC drive control with ever lower power dissipation hardware and ever more accurate control structures. The electrical drive controls become more accurate in the sense that not only are the DC current and voltage controlled but also the three phase currents and voltages are managed by so-called vector controls. This document describes the most efficient form of vector control scheme: the Field Orientated Control. It is based on three major points: the machine current and voltage space vectors, the transformation of a three phase speed and time dependent system into a two co-ordinate time invariant system and effective Pulse Width Modulation pattern generation. Thanks to these factors, the control of AC machine acquires every advantage of DC machine control and frees itself from the mechanical commutation drawbacks. Furthermore, this control structure, by achieving a very accurate steady state and transient control,

leads to high dynamic performance in terms of response times and power conversion. These different aspects are discussed in the following chapters.

1.2 Field Oriented Control

(FOC) is one of the most modern techniques used to control the speed of 3 phase induction motor (IM) as most of industrial applications which use this kind of motors require speed variation to perform it's task. The main problem that was hinder the usage of IM is the difficulty to control it's speed because of the coupling between rotor and stator field.

FOC based on three major points: the machine current and voltage space vectors, the transformation of a 3 phase speed and time dependent system into a two co-ordinate time invariant system using programmable digital signal processor (DSP). This decouples the torque and flux producing components of the stator currents allowing the induction motor to be controlled in much the same was as a separately excited DC machine .Thanks to these factors, the control of AC machine acquires the advantage of DC machine control and frees itself from the mechanical commutation drawbacks.

1.3 BASIC CONSTRUCTION

Like most motors, an AC induction motor has a fixed outer portion, called the stator and a rotor that spins inside with a carefully engineered air gap between the two. Virtually all electrical motors use magnetic field rotation to spin their rotors. A three-phase AC induction motor is the only type where the rotating magnetic field is created naturally in the stator because of the nature of the supply. DC motors depend either on mechanical or electronic commutation to create rotating magnetic fields. A single-phase AC induction motor depends on extra electrical components to produce this rotating magnetic field. Two sets of electromagnets are formed inside any motor.

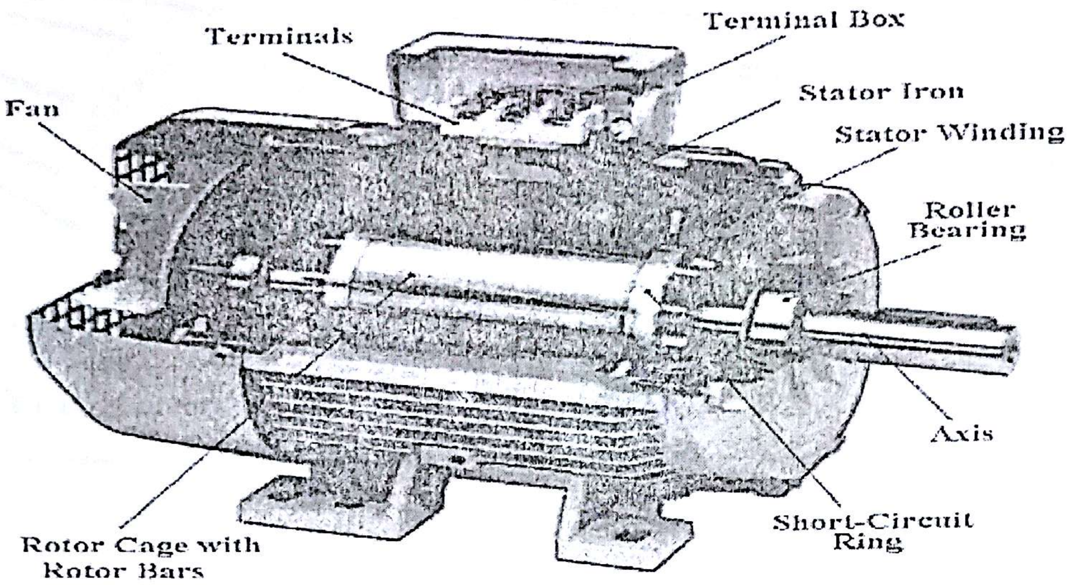


FIGURE (1.1) BASIC CONSTRUCTION OF I.M.

1.3.1 Stator

The stator is made up of several thin laminations of aluminum or cast iron. They are punched and clamped together to form a hollow cylinder (stator core) with slots as shown in Figure 1. Coils of insulated wires are inserted into these slots. Each grouping of coils, together with the core it surrounds, forms an electromagnet (a pair of poles) on the application of AC supply. The number of poles of an AC induction motor depends on the internal connection of the stator windings. The stator windings are connected directly to the power source. Internally they are connected in such away, that on applying AC supply, a rotating magnetic field is created.

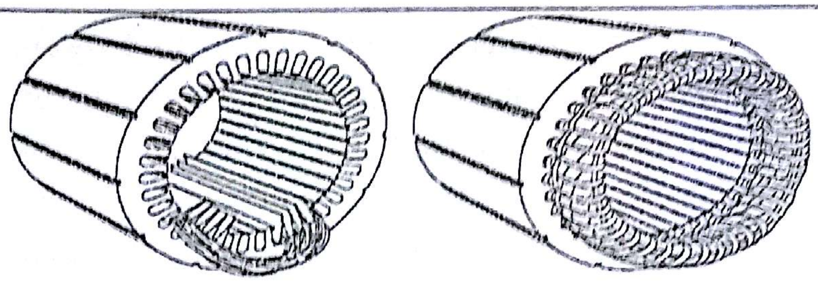


FIGURE (1.2)

A TYPICAL STATOR

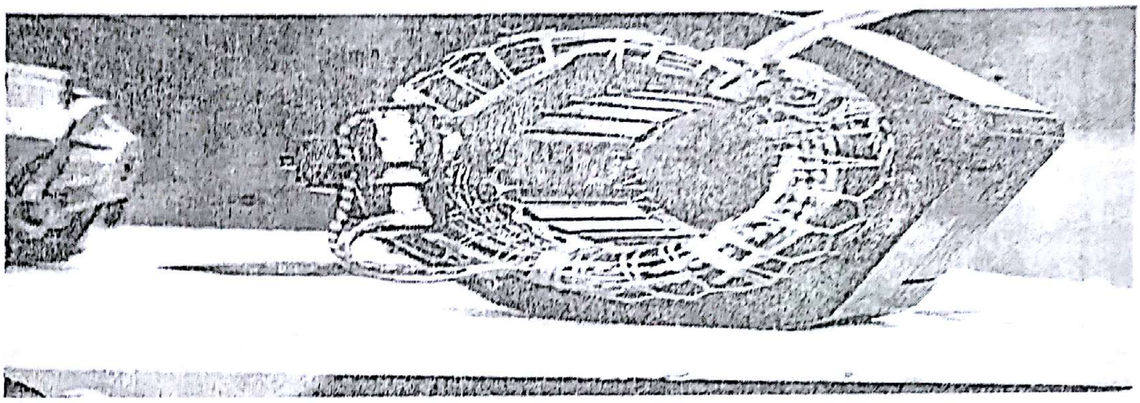


FIGURE (1.3) TYPICAL STATOR

1.3.2 Rotor

The rotor is made up of several thin steel laminations with evenly spaced bars, which are made up of aluminum or copper, along the periphery. In the most popular type of rotor (squirrel cage rotor), these bars are connected at ends mechanically and electrically by the use of rings. Almost 90% of induction motors have squirrel cage rotors. This is because the squirrel cage rotor has a simple and rugged construction. The rotor consists of a cylindrical laminated core with axially placed parallel slots for carrying the conductors. Each slot carries a copper, aluminum, or alloy bar. These rotor bars are permanently short-circuited at both ends by means of the end rings, as shown in Figure 2. This total assembly resembles the look of a squirrel cage, which gives the rotor its name. The rotor slots are not exactly parallel to the shaft. Instead, they are given

askew for two main reasons. The first reason is to make the motor run quietly by reducing magnetic hum and to decrease slot harmonics. The second reason is to help reduce the locking tendency of the rotor. The rotor teeth tend to remain locked under the stator teeth due to direct magnetic attraction between the two. This happens when the number of stator teeth are equal to the number of rotor teeth. The rotor is mounted on the shaft using bearings on each end; one end of the shaft is normally kept longer than the other for driving the load. Some motors may have an accessory shaft on the non-driving end for mounting speed or position sensing devices. Between the stator and the rotor, there exists an air gap, through which due to induction, the energy is transferred from the stator to the rotor. The generated torque forces the rotor and then the load to rotate. Regardless of the type of rotor used, the principle employed for rotation remains the same.

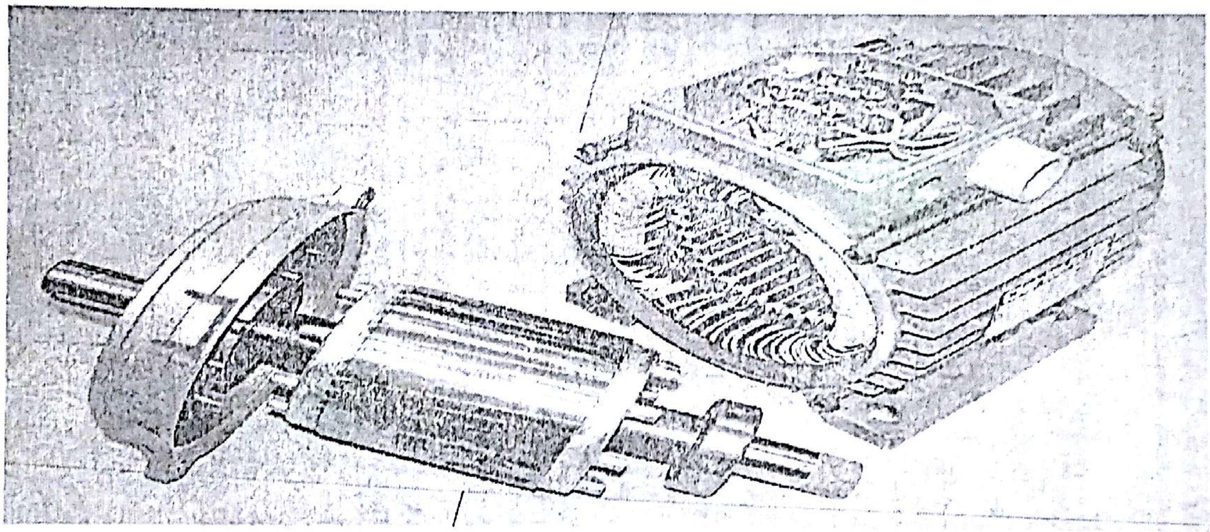


FIGURE (1.4) TYPICAL ROTOR

The rotor of an induction machine is different from other types of machine that we have considered so far: there is no requirement for a power source on the rotor. There are two general types of rotors:
The squirrel-cage rotor
The wound (or slip ring) rotor.

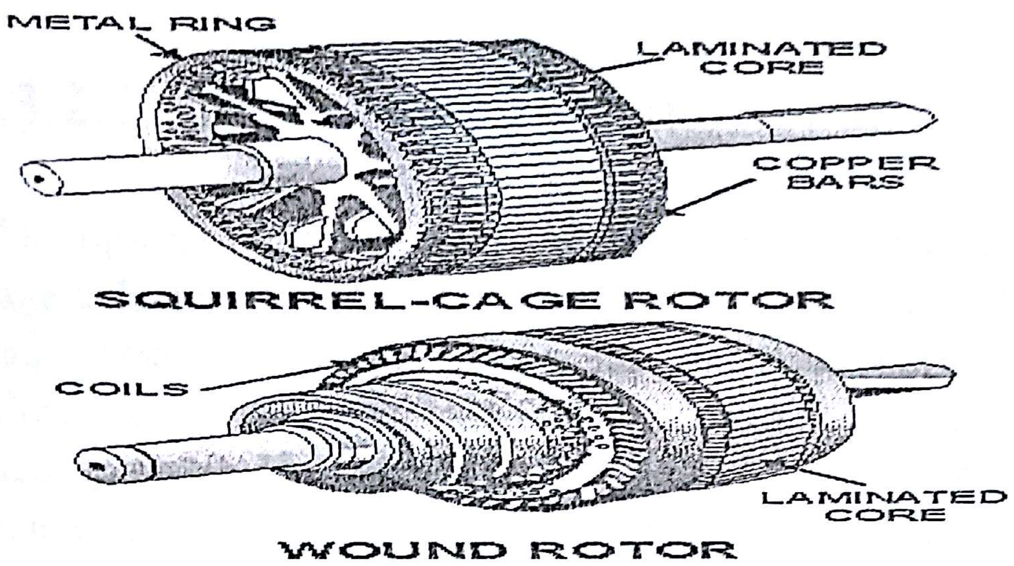


FIGURE (1.5) TYPE OF ROTOR

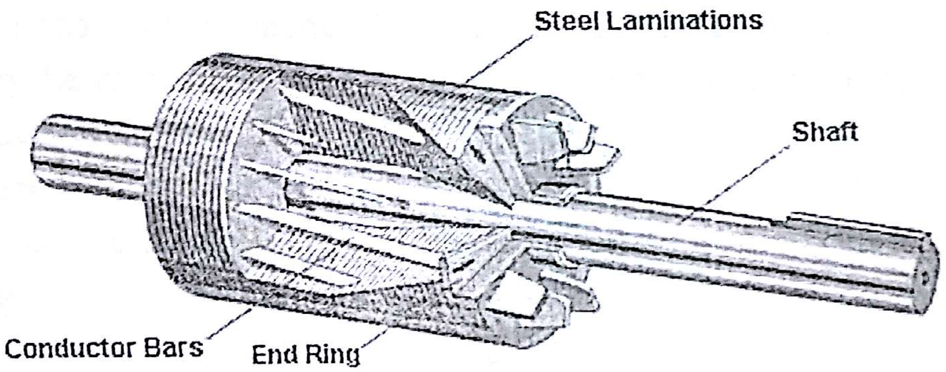


FIGURE (1.6) SQUIRREL CAGE ROTOR

1.3.2.1 In the squirrel-cage rotor

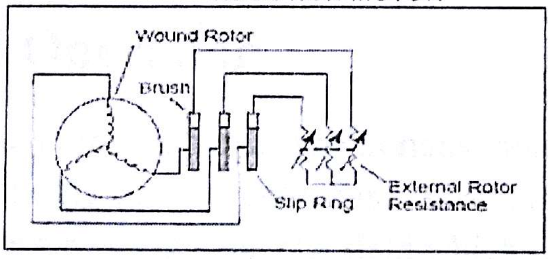
, the rotor winding consists of single copper or aluminum bars placed in the slots and short-circuited by end rings on both sides of the rotor. Almost 90% of the three-phase AC Induction motors are of this type. Here, the rotor is of the squirrel cage type and it works as explained earlier. The power ratings range from one-third to several hundred horse

power in the three-phase motors. Motors of this type, rated one horsepower or larger, cost less and can start heavier loads than their single-phase counterparts.]

1.3.2.2 In the wound rotor,

The slip-ring motor or wound-rotor motor is a variation of the squirrel cage induction motor. While the stator is the same as that of the squirrel cage motor, it has a set of windings on the rotor which are not short-circuited, but are terminated to a set of slip rings. These are helpful in adding external resistors and contactors. The slip necessary to generate the maximum torque(pull-out torque) is directly proportional to the rotor resistance. In the slip-ring motor, the effective rotor resistance is increased by adding external resistance through the slip rings. Thus, it is possible to get higher slip and hence, the pull-out torque at a lower speed. A particularly high resistance can result in the pull-out torque occurring at almost zero speed, providing a very high pull-out torque at a low starting current. As the motor accelerates, the value of the resistance can be reduced, altering the motor characteristic to suit the load requirement. Once the motor reaches the base speed, external resistors are removed from the rotor. This means that now the motor is working as the standard induction motor. This motor type is ideal for very high inertia loads, where it is required to generate the pull-out torque at almost zero speed and accelerate to full speed in the minimum time with minimum current draw.

TYPICAL WOUND-ROTOR INDUCTION MOTOR



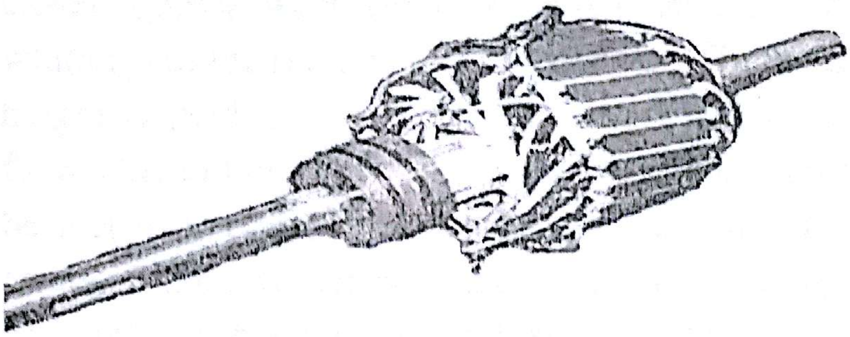


FIGURE (1.7) TYPICAL WOUND ROTOR

The downside of the slip ring motor is that slip rings and brush assemblies need regular maintenance, which is a cost not applicable to the standard cage motor. If the rotor windings are shorted and a start is attempted (i.e., the motor is converted to a standard induction motor),it will exhibit an extremely high locked rotor current –typically as high as 1400% and a very low locked rotor torque, perhaps as low as 60%. In most applications, this is not an option. Modifying the speed torque curve by altering the rotor resistors, the speed at which the motor will drive a particular load can be altered. At full load, you can reduce the speed effectively to about 50% of the motor synchronous speed, particularly when driving variable torque/variable speed loads, such as printing presses or compressors. Reducing the speed below 50%results in very low efficiency due to higher power dissipation in the rotor resistances. This type of motor is used in applications for driving variable torque/variable speed loads, such as in printing presses, compressors, conveyer belts, hoists and elevators.

1.4 Operation

In both induction and synchronous motors, the stator is powered with alternating current (polyphase current in large machines) and designed to create a rotating magnetic field which rotates in time with the AC oscillations. In a synchronous motor, the rotor turns at the same rate as the stator field. By contrast, in an induction motor the rotor rotates at a slower speed than the stator field. Therefore the magnetic field through the rotor is changing (rotating). The rotor has windings in the form of

closed loops of wire. The rotating magnetic flux induces currents in the windings of the rotor as in a transformer. These currents in turn create magnetic fields in the rotor, that interact with (push against) the stator field. Due to Lenz's law, the direction of the magnetic field created will be such as to oppose the change in current through the windings. The cause of induced current in the rotor is the rotating stator magnetic field, so to oppose this the rotor will start to rotate in the direction of the rotating stator magnetic field to make the relative speed between rotor and rotating stator magnetic field zero.

For these currents to be induced, the speed of the physical rotor must be lower than that of the stator's rotating magnetic field (n_s), or the magnetic field would not be moving relative to the rotor conductors and no currents would be induced. As the speed of the rotor drops below synchronous speed, the rotation rate of the magnetic field in the rotor increases, inducing more current in the windings and creating more torque. The ratio between the rotation rate of the magnetic field as seen by the rotor (slip speed) and the rotation rate of the stator's rotating field is called "*slip*". Under load, the speed drops and the slip increases enough to create sufficient torque to turn the load. For this reason, induction motors are sometimes referred to as asynchronous motors.

1.5 Speed of an Induction Motor

The magnetic field created in the stator rotates at a synchronous speed (*NS*).

EQUATION 1:
Figure

$$Ns = \frac{12oF}{P}$$

where:
NS = the synchronous speed of the stator magnetic field in RPM
P = the number of poles on the stator
f = the supply frequency in Hertz

(1.1)

The magnetic field produced in the rotor because of the induced voltage is alternating in nature. To reduce the relative speed, with respect to the stator, the rotor starts running in the same direction as that of the stator flux and tries to catch up with the rotating flux. However, in practice, the rotor never succeeds in "catching up" to the stator field. The rotor runs slower than the speed of the stator field. This speed is called the Base Speed (*Nb*). The difference between *NS* and *Nb* is called the slip. The slip varies with the load. An increase in load will cause the rotor to slow down or increase slip. A decrease in load will cause the rotor to speed up or decrease slip. The slip is expressed as a percentage and can be determined with the following formula:

EQUATION 2:

(1.2)

$$\% \, Slip = \frac{N_s - N_b}{N_s} * 10o$$

where:
NS = the synchronous speed in RPM
Nb = the base speed in RPM

1.6 Equivalent Circuit

We have seen that induction machines (as you might guess from the name) operate on the principle of induced currents. There are still two magnetic fields, one from each of the rotor and stator, but the rotor field is induced by the stator field. Effectively, we can think of the induction machine as a rotating transformer. The stator is like the primary of a transformer and creates the initial field, inducing voltages and currents in the secondary rotor winding. The fundamental differences from a stationary transformer are:

- The secondary rotates
- There is an air gap, therefore more mmf is needed for a given flux density
- The secondary voltage and frequency depend on speed

As an aside, a wound rotor induction machine can actually be used as a variable frequency transformer. For instance, a 60Hz system connected to the primary of an induction machine can transfer power to a 50hz system connected to the rotor if the machine is mechanically driven at a slip of 5/6.

The per-phase equivalent circuit model for an induction machine in steady state operation supplied by a balances three-phase supply is based on the transformer model shown below

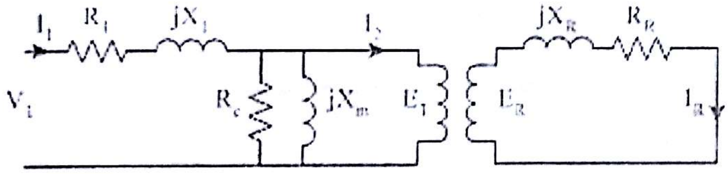


Figure (1.8) EQUIVALENT CIRCUIT OF I.M.

In the diagram above,

- V_1 = Phase RMS Voltage
- I_1 = Stator Phase Current
- R_1 = Stator Winding Resistance
- X_1 = Stator Winding Leakage Reactance
- X_m = Magnetizing Reactance
- R_c = Core Loss Resistance
- E_1 = Air Gap Voltage
- I_2 = Rotor Current Referred to Stator

- E_R = Rotor Induced Voltage (Actual)
- I_R = Rotor Current Voltage (Actual)
- X_R = Rotor Leakage Reactance (Actual)
- R_R = Rotor Resistance (Actual)

1.6.1 Rotor Circuit

leakage reactance X_R both depend on slip. To simplify the model we can define them both in terms of their values when the speed is zero, slip s = 1.0

$$E_R = SE_{n} \qquad (1.3)$$

$$X_R = SX_{\infty} \qquad (1.4)$$

where

- E_{R0} = induced voltage at standstill
- X_{R0} = rotor leakage reactance at standstill

With the above definitions we can write the equation for actual rotor current as

$$I_R = \frac{E_R}{R_R + JX_R} = \frac{SE_{Ro}}{R_R + JSX_{RO}} = \frac{E_{Ro}}{R_R/S + JX_{Ro}} \qquad (1.5)$$

and the transformer model may be re-drawn as

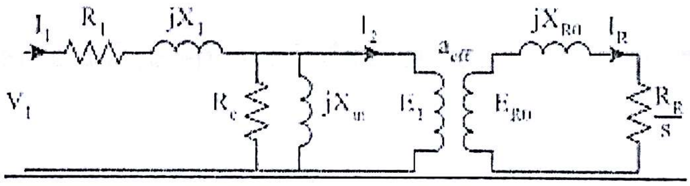


Figure (1.9) ROTOR CIRCUIT

In the above diagram, the effective turns ratio a_{eff} is constant and equal to the effective turns ratio at standstill. In a would rotor machine, a_{eff},X_{R0} and R_R can be measured. In a cage machine these parameters cannot be directly determined, there is no method to directly measure voltages or currents on the rotor. To overcome this difficulty, the rotor (secondary) circuit can be referred to the stator (primary) side.

1.6.2 Full Equivalent Circuit Model

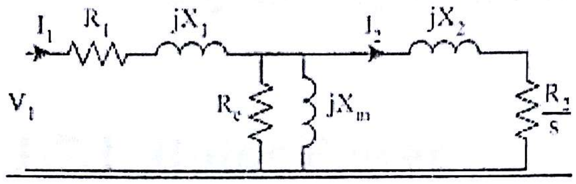


Figure (1.10) FULL EQUIVALENT CIRCUIT

In the above circuit

- $R_2 = a^2_{eff}R_R$, the rotor resistance referred to the stator
- $X_2 = a^2_{eff}X_{R0}$, the rotor leakage reactance referred to the stator

The symbols used in induction machine models vary depending on the text and the context in which the circuit is being used. R_I, R_o, R_{fe}, R_m can all be found as references to the iron loss resistance. In some texts (especially from Europe), R_2, X_2 refer to actual rotor values with R'_2, X'_2 used for referred values. In drives texts, it is common to find R_s, R_r for stator resistance and rotor resistance referred to the stator.

1.7 Power & Torque

The input power to a three-phase induction machine is given by

Output power can be found by subtracting the losses from the input power

Losses

1. Stator Copper Loss. The stator resistive losses

$$P_{cu1} = 3I_1^2R_1 \tag{1.7}$$

2. Rotor Joule Loss. The rotor resistive losses. This is often called rotor copper loss, but since the rotor conductors are aluminum, rotor joule loss is the more correct terminology.

$$P_{cu2} = 3I_2^2 R_2 \quad (1.8)$$

3. Core Loss, or Iron Loss. The losses due to eddy current and hysteresis losses in the laminations. This can be calculated using the resistor R_c. Often, core losses are grouped with friction and windage and stray loss as rotational losses.

1.7.1 Rotor Power

The power transferred to the rotor is called the "Air gap Power". Consider the equivalent circuit below (the core loss resistance has been removed and core losses grouped into rotational loss).

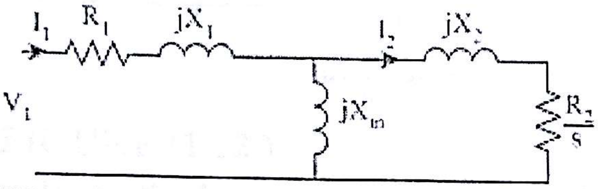


FIGURE (1.11)

From the above circuit, it can be seen that the total power transfer to the rotor is given by

$$P_g = \frac{3I_2^2 R_2}{S} \quad (1.9)$$

To find the power converted to the mechanical system the rotor joule loss must be subtracted from the total rotor power

$$P_{conv} = P_{gap} - P_{RCL}$$

$$P_{conv} = \frac{3I_2^2 R_2}{s} - 3I_2^2 R_2$$

$$P_{conv} = 3I_2^2 R_2 \frac{(1-s)}{s} \quad (1.10)$$

From the above equations, it can be seen that power converters to the mechanical system is a function of the air gap power and slip:

$$P_{conv} = (1-s) P_{gap} \quad (1.11)$$

Final output power may be obtained by subtracting the rotational loss from P_{conv}.

$$P_{out} = P_{conv} - P_{rotational} \quad (1.12$$

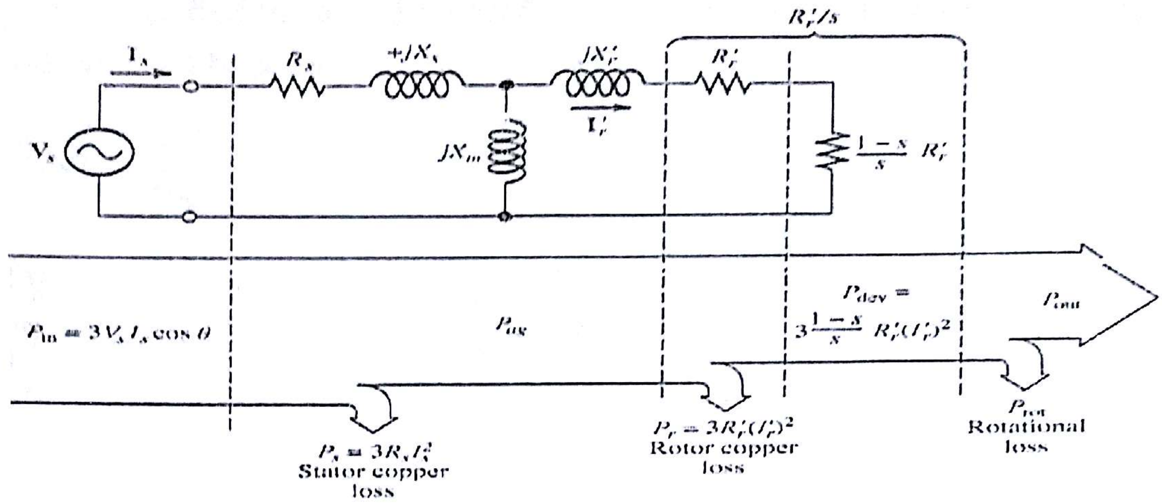


FIGURE (1.12)
Schematic diagram of the power flow

1.7.2 Torque

As with all rotating mechanical systems in steady state, torque can be found from the power and mechanical speed

$$\tau = \frac{P_{mech}}{\omega_m} \qquad (1.13)$$

In the case of an induction machine, the electromagnetic torque generated by the machine can be found using

$$\tau = \frac{P_{conv}}{\omega_m} \quad \tau = \frac{(1-s)P_{ag}}{(1-s)\omega_s} \qquad (1.14)$$

which gives

$$\tau = \frac{P_{ag}}{\omega_s} \qquad (1.15)$$

Writing the torque in terms of the rotor current:

$$\tau = \frac{3I_2^2 R_2}{s\omega_s} \qquad (1.16)$$

Finally, to find the available shaft torque after rotational losses, the output power must be used.

$$\tau_{shaft} = \frac{P_{out}}{\omega_m} \qquad (1.17)$$

$$T = \frac{P_g}{\omega_S} = \frac{3I_2'^2 \frac{R'_2}{S}}{\frac{2\pi N_S}{60}} \qquad (1.18)$$

$$K = \frac{3 \times 60}{2\pi N_S} \qquad (1.20)$$

By reference to the equivalent circuit the current I'_2 can be calculated as follow:

$$I'_2 = \frac{V_1}{Z_{eq}} = \frac{V_1}{\sqrt{\left[R_1 + {R'_2}/{S}\right]^2 + X_{eq}^2}} \qquad (1.21)$$

$$T = K \frac{V_1^2}{\left[R_1 + {R'_2}/{S}\right]^2 + X_{eq}^2} \frac{R'_2}{S} \qquad (1.22)$$

The starting torque can be calculated when ,S=1

1.8 TORQUE EQUATION GOVERNING MOTOR OPERATION

The motor load system can be described by a fundamental torque equation.

EQUATION 3:

$$T - T_l = J\frac{d\omega_m}{d_t} + \omega_m\frac{dJ}{dt}$$

where:
T = the instantaneous value of the developed motor torque (*N-m* or *lb-inch)*
Tl = the instantaneous value of the load torque
(*N-m* or *lb-inch)*
□*m* = the instantaneous angular velocity of the motor shaft (rad/sec)
J = the moment of inertia of the motor – load system (*kg-m2* or *lb-inch2*)

(1.24)

For drives with constant inertia, (*dJ/dt*) = 0. Therefore, the equation would be:

EQUATION 4:

$$T = T_l + J\frac{d\omega_m}{dt} \tag{1.25}$$

This shows that the torque developed by the motor is counter balanced by a load torque, *Tl* and a dynamic torque, *J*(*dm*/*dt*). The torque component, *J*(*dm*/*dt*), is called the dynamic torque because it is present only during the transient operations. The drive accelerates or decelerates depending on whether *T* is greater or less than *Tl*. During acceleration, the motor should supply not only the load torque, but an additional torque component, *J*(*dm*/*dt*), in order to overcome the drive inertia. In drives with large inertia, such as electric trains, the motor torque must exceed the load torque by a large amount in order to get adequate acceleration.

In drives requiring fast transient response, the motor torque should be maintained at the highest value and the motor load system should be designed with the lowest possible inertia. The energy associated with the dynamic torque, *J(dm/dt)*, is stored in the form of kinetic energy (KE) given by, *J(□□m/2)*. During deceleration, the dynamic torque, *J(dm/dt)*, has a negative sign. Therefore, it assists the motor developed torque *T* and maintains the drive motion by extracting energy from the stored kinetic energy. To summarize, in order to get steady state rotation of the motor, the torque developed by the motor (*T*) should always be equal to the torque requirement of the load (*Tl*). The torque-speed curve of the typical three-phase induction motor is shown in Figure

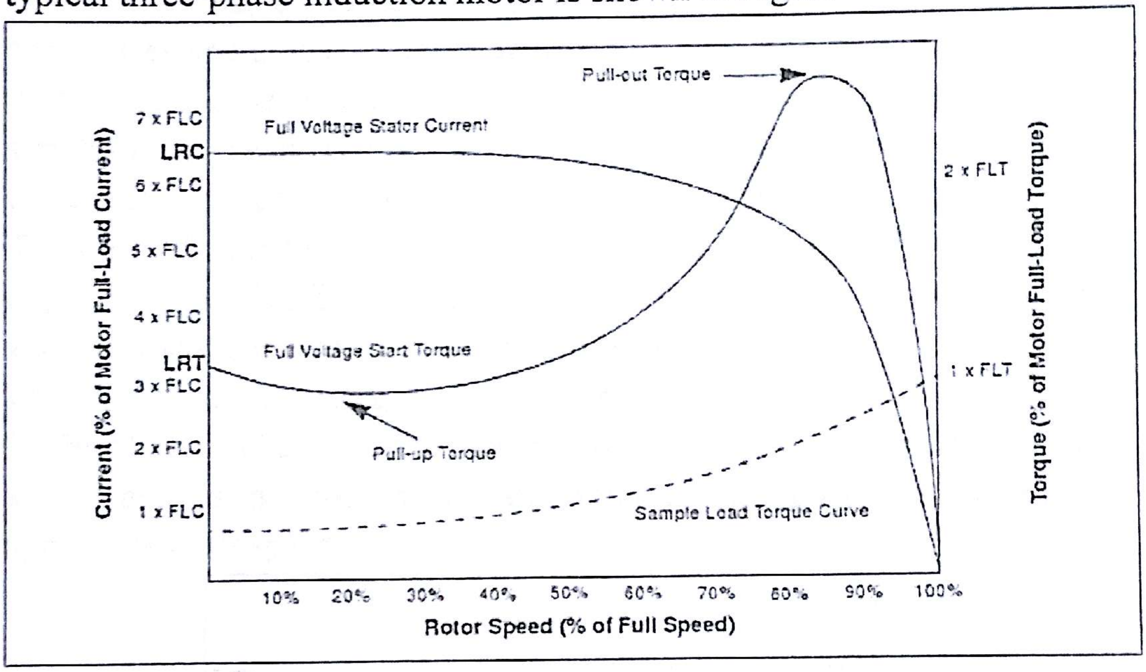


FIGURE (1.13) Relation between current and rotor speed &Relation between torque and rotor speed

1.9 STARTING CHARACTERISTIC

Induction motors, at rest, appear just like a short circuited transformer and if connected to the full supply voltage, draw a very high current known as the "Locked Rotor Current." They also produce torque which is known as the "Locked Rotor Torque". The Locked Rotor Torque (LRT) and the Locked Rotor Current (LRC) are a function of the terminal voltage of the motor and the motor design. As the motor accelerates, both

the torque and the current will tend to alter with rotor speed if the voltage is maintained constant. The starting current of a motor with a fixed voltage will drop very slowly as the motor accelerates and will only begin to fall significantly when the motor has reached at least 80% of the full speed. The actual curves for the induction motors can vary considerably between designs but the general trend is for a high current until the motor has almost reached full speed. The LRC of a motor can range from 500% of Full-Load Current (FLC)to as high as 1400% of FLC. Typically, good motors fall in the range of 550% to 750% of FLC. The starting torque of an induction motor starting with a fixed voltage will drop a little to the minimum torque, known as the pull-up torque, as the motor accelerates and then rises to a maximum torque, known as the breakdown or pull-out torque, at almost full speed and then drop to zero at the synchronous speed. The curve of the start torque against the rotor speed is dependant on the terminal voltage and the rotor design.

The LRT of an induction motor can vary from as low as60% of FLT to as high as 350% of FLT. The pull-up torque can be as low as 40% of FLT and the break down torque can be as high as 350% of FLT. Typically, LRTs for medium to large motors are in the order of 120% of FLT to 280% of FLT. The PF of the motor at start is typically 0.1-0.25, rising to a maximum as the motor accelerates and then falling again as the motor approaches full speed.

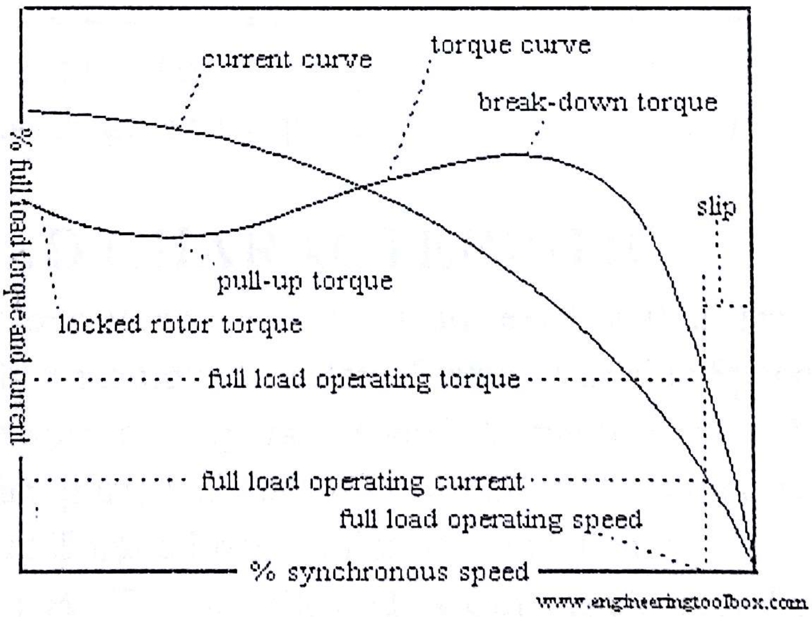


FIGURE (1.14) Relation between torque& current and synch speed

1.10 RUNNING CHARACTERISTIC

Once the motor is up to speed, it operates at a low slip, at a speed determined by the number of the stator poles. Typically, the full-load slip for the squirrel cage induction motor is less than 5%. The actual full-load slip of a particular motor is dependant on the motor design. The typical base speed of the four pole induction motor varies between 1420 and 1480 RPM at 50 Hz, while the synchronous speed is 1500 RPM at 50 Hz. The current drawn by the induction motor has two components : reactive component (magnetizing current)and active component (working current). The magnetizing current is independent of the load but is dependant on the design of the stator and the stator voltage. The actual magnetizing current of the induction motor can vary, from as low as 20% of FLC for the large two pole machine, to as high as 60% for the small eight pole machine. The working current of the motor is directly proportional to the load. The tendency for the large machines and high-speed machines is to exhibit a low magnetizing current, while for the low-speed machines and small machines the tendency is to exhibit a high magnetizing current. Atypical medium sized four pole machine has a magnetizing current of about 33% of FLC.A low magnetizing current indicates a low iron loss, while a high magnetizing current indicates an increase in iron loss and a resultant reduction in the operating efficiency. Typically, the operating efficiency of the induction motor is highest at 3/4 load and varies from less than 60% for small low-speed motors to greater than 92% for large high-speed motors. The operating PF and efficiencies are generally quoted on the motor data sheets.

1.11 LOAD CHARACTERISTIC

In real applications, various kinds of loads exist with different torque-speed curves. For example, Constant Torque, Variable Speed Load (screw compressors, conveyors, feeders), Variable Torque, Variable Speed Load (fan, pump), Constant Power Load (traction drives), Constant Power, Constant Torque Load (coiler drive) and High Starting/Breakaway Torque followed by Constant Torque Load (extruders, screw pumps).The motor load system is said to be stable when the developed motor torque is equal to the load torque requirement. The motor will operate in a steady state at a fixed speed. The response of the

motor to any disturbance gives us an idea about the stability of the motor load system. This concept helps us in quickly evaluating the selection of a motor for driving a particular load. In most drives, the electrical time constant of the motor is negligible as compared to its mechanical time constant. Therefore, during transient operation, the motor can be assumed to be in an electrical equilibrium, implying that the steady state torque-speed curve is also applicable to the transient operation. As an example, Figure (1.15) shows torque-speed curves of the motor with two different loads. The system can be termed as stable, when the operation will bere stored after a small departure from it, due to a disturbance in the motor or load. For example, disturbance causes a reduction of □□*m* in speed. In the first case, at a new speed, the motor torque (*T*) is greater than the load torque (*Tl*). Consequently,
the motor will accelerate and the operation will be restored to X. Similarly, an increase of □□*m* in the
speed, caused by a disturbance, will make the load torque (*Tl*) greater than the motor torque (*T*), resulting in a deceleration and restoration of the point of operation to X. Hence, at point X, the system is stable. In the second case, a decrease in the speed causes the load torque (*Tl*) to become greater than the motor torque (*T*), the drive decelerates and the operating point moves away from Y. Similarly, an increase in the speed will make the motor torque (*T*) greater than the load torque (*Tl*), which will move the operating point further away from Y. Thus, at point Y, the system is unstable. This shows that, while in the first case, the motor selection for driving the given load is the right one; in the second case, the selected motor is not the right choice and requires changing for driving the given load. The typical existing loads with their torque-speed curves are described in the following sections.

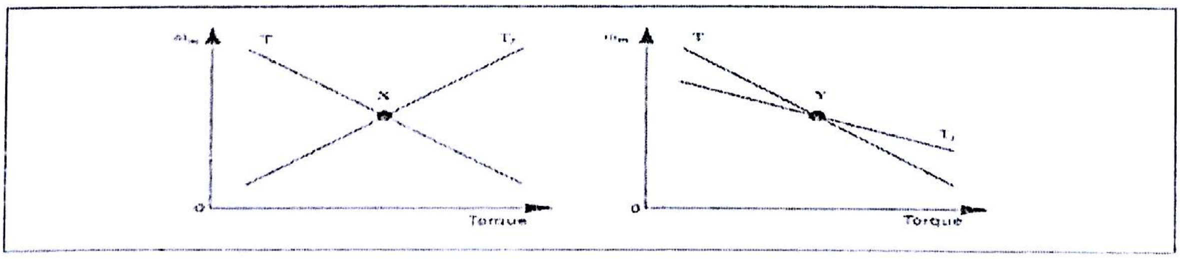


FIGURE (1.15) Relation between speed and torque